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The Radioactive Particle Tracking Technique for Validation of CFD simulations in SMR Designs

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1. Introduction

Small Modular Reactors (SMRs) are nuclear plants with size and power smaller than the earlier generations of nuclear reactors. While the power of SMRs is no more than 300 MWe, the average power of a traditional nuclear power plant is about 1,000 MWe. SMRs are compact instalations which main componentes are built in modules in a factory out of the installation site. Then, the modules are transported to the final site, interconnected (modularization process) and the plant starts operating for local energy distribution, desalination or support for other industrial processes. Among the SMR projects under development in the world, the most reliable have passive safety devices that use natural convection systems for cooling in order to reduce the risk of accidents in the reactor core and the release of radioisotopes into the environment. [1].

Computational Fuid Dynamics (CFD) is applied to the design of nuclear power plants and nowadays SMR projects also uses this tool. The uncertainty quantification (UQ) is an essential part of CFD simulations to estimate design parameters of the plant or parameters related to nuclear safety. It consists of identifying the various sources of uncertainty so that each one can be quantified. The two types of methods developed and used for UQ of system codes are [2]:

a) Propagation of the uncertainty
b) Extrapolation of accuracy

Scaling of an experiment is the process of demonstrating how and to what extent the simulation of a physical process, such as a reactor in the transient state, in a reduced-scale experiment, can be representative of the real process. The scale associated with the CFD application is part of the uncertainty assessment of the CFD code, being a preliminary step in UQ. In this process, scale and uncertainty are connected to the technique of validation and verification (V&V).

Verification is a process to assess the accuracy of the software and the numerical accuracy of the solution for a given physical model defined by a set of equations.

Validation is necessary to give us confidence in the ability of a computational code to predict the values of safety parameters or parameters of interest and to quantify the precision and accuracy of those values. In this sense, validation can be conducted by developers or users of the code, being called development evaluation in the first case or independent evaluation in the second case. In both cases, it is necessary to employ experiments to check some parameters related to the transport phenomena.

The results of validation step can be used to determine the uncertainty of some constitutive of the code and has been registered in validation matrices. A validation matrix is a set of experimental data selected for the systematic validation of a code. The validation matrix usually includes: nuclear plant data, basic tests, separate effects tests or single effect tests (SETs), integral effect tests (IETs) or combined effects tests (CETs).

The solution of a thermo-hydraulic problem in a nuclear reactor can be purely experimental, that is, the tests can estimate what would happen in the reactor with enough precision and reliability. Generally, test and simulation tools are used together to solve the problem so that simulation is used to extrapolate reactor situations, as scaling up and the degree of confidence in the extrapolation is part of the design. Indeed, all types of thermo-hydraulic codes have intrinsic limitations related to phenomena that aren´t modelled: they use closure laws obtained for steady established flows in transient non-established flows and the phenomena associated to non-establishment or transient effects are not modelled. CFD codes also use turbulence models that never describe all geometrical effects in complex industrial geometries. Therefore, as consequence of these sources of uncertainty in the codes, mainly those related to non-modelled effects, the validation of the CFD tool on scaled IETs is mandatory

Since the last three decades, there has been a growing interest among researchers in applying radioactive particle tracking (RPT) technique to investigate hydrodynamics in various multiphase flow systems due to its versatility in probing different kinds of multiphase reactors, high enough accuracy for most practical applications and, certainly, the richness of the information provided [3]. The basic principle of RPT is the use of one or more particles emitting highly penetrative gamma radiation as markers of the phases whose velocities need to be mapped. In case of liquid-phase tracking, the tracer particle generally has a microsphere shape and should be neutrally buoyant with regard to the liquid. For solid-phase tracking, the density of the tracer particle, as well as its nominal size and shape, are properties that have to mimic the same properties of the solids constituting the flow.

In RPT experiments, the path of the tracer particle is tracked with the help of scintillation detectors previously placed in strategic positions around the unit under investigation. As the radioactive tracer particle moves along with the flow of interest, its successive positions are linked with the time series of photon counts recorded in each detector. Then, solving the inverse problem, it is possible to estimate those positions, trace the trajectory described by the particle inside the fluid and calculate, through the difference in time between each pair of successive positions of the particle, the instantaneous velocity as a function of time. From these information, a detailed analysis of the flow field can be extracted by calculating other flow-measuring quantities, which include three-dimensional mean velocity fields, kinetic energies of turbulence, shear stresses, dispersion coefficients and other metrics that can be achieved by analyzing the position and velocity time series.

The aim of this work was to evaluate the feasibility of the RPT technique [4] to track successive positions of a radioactive microsphere [5] in a full-scale water tank using only four scintillation detectors. A simple trajectory of the particle within a natural circulation safety system was modeled using the Monte Carlo N Particle Transport (MCNP) code. The dimensions of the tank, the positions of the radioactive particle and the gamma radiation detection and counting system are the main variables. Then, the counts from MCNP entered into the RPT algorithm that was run to reconstruct that trajectory using its own model of the radioactive source in the tank and gamma radiation detection system.

2. Methodology

The first part of the research was the modeling of the particle trajectory using the MCNP code [6]. The system consisted of a cylindrical water-filled polypropylene tank (280 cm high, 80 cm wide and 1 cm thick), four NaI:Tl detectors, size 5"x5", 90^0 degrees apart, positioned at 60 cm from the wall of the tank, and a point source of Sc^{46}, which was positioned at seven different points inside the tank, forming a semi-closed trajectory model. The choice of the dimensions 5"x5" as detector size, the arrangement of detectors around the tank and the Sc^{46} as radioisotope was based on the most up-to-date study for optimization of RPT designs [7]. Figure 1 is the representation of the arrangement of detectors in the MCNP code. The simulated positions of the trajectory are described in Table I.

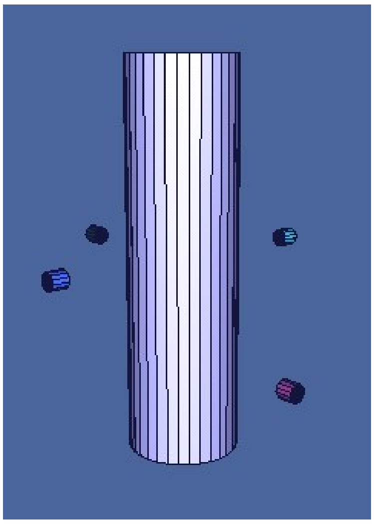

Figure 1. Representation of the tank and the arrangement of detectors in MCNP code.

Table I. Coordinates of the positions of the simulated trajectory (cm).

Position	X	Y	Z
1	-20	10	70
2	-38	20	140
3	-20	10	210
4	0	0	270
5	20	-10	210
6	38	-20	140
7	20	-10	70

Other important input parameters of the model were dimensions of the tank, detector material, the composition of the media surrounding the tank and the selected photo peak of gamma radiation.
In Table II, the configuration of the detection system is showed as a function of the Z coordinate of each detector. Detectors were positioned at the same distance d = 60 cm from the face of detector to the wall of the tank and the chosen photo peak of ^{46}Sc was 0.899 MeV.
The output parameter of the MCNP code that was selected for this work are the counts of the photons that hit each detector and were absorbed into the crystal. These counts were set to be equal to or less than 90,000, which corresponds to 90% of the saturation limit of a NaI:Tl detector (10^5 counts). Finally, these counts are included as input variables to the RPT algorithm that estimates the reconstructed positions of the radioactive particle. Except for the radioactive source counts of known Activity, provided from the MCNP code, all other input parameters of the RPT code were achieved from the physical properties of the media. The output variables of the RPT code are the instantaneous source positions or the source velocities. Particle trajectory data can be plotted in different graphic forms, according to the user's interest.
Intentionally, the MCNP code model considered the incidence of 0.899 MeV photons on the face and sides of

the detectors, that is, all sides of the detector are unshielded against radiation. On the other hand, the positions reconstructed by the RPT code were estimated for the detector model with a lead shield around it, as in a real test.

Table II. Description of the spatial distribution of the detectors, along the Z-axis (cm), at a distance d=60.0 cm from the tank.

Detector 1	Detector 2	Detector 3	Detector 4
70.0	140.0	140.0	140.0

3. Results and Discussion

For each position of the particle, relative errors between reconstructed trajectory and the original (simulated) trajectory were calculated and described in Table III. Coordinates with bad absolute errors are marked in red and those with good absolute errors are marked in blue. Only reconstructed positions 2 and 3 of the source have blue errors below 5% and only position 3 have no red errors, that is, a high dispersion of errors is observed as viewed on the graph of Figure 2. Analysing Table III, the bad reconstructions are concentrated at Y or Z coordinates, far from the faces of detectors 2, 3 and 4 (Z= 140.0 cm) or at Z coordinates, far from the face of detector 1(Z= 70.0 cm).

Table III. Calculation of the relative errors among simulated and reconstructed trajectories

	Simulated Coordinates (cm)			Reconstructed Coordinates (cm)			
Position	X	Y	Z	X	Y	Z	Relative Error (%)
1	-20	10	70	-16	6	92	30.91
2	-38	20	140	-36	14	140	4.32
3	-20	10	210	-22	12	210	1.34
4	0	0	278	0	0	262	5.76
5	20	-10	210	18	-8	194	7.69
6	38	-20	140	38	-8	138	8.31
7	20	-10	70	18	-14	84	20.0
					Mean		11.19

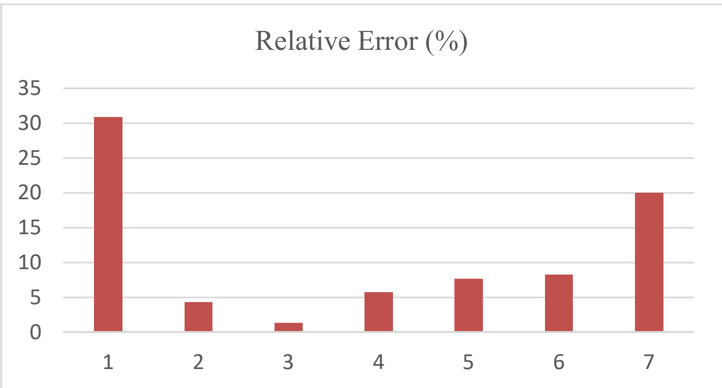

Figure 2. Comparison of the relative errors among positions

The results are consequence of the MCNP model, that is, the geometric efficiencies of detectors are increased for all source positions due to a large fraction of photons reaches the unshielded sides. As the RPT model doesn´t consider photons reaching the sides of the detectors, bad reconstructed positions are estimated at distances from the detectors that are smaller than the positions simulated on MCNP because counts are inversely proportional to the square of source-detector distance. Therefore, the results are consistent with detector counts higher than the right counts, causing errors as bad as that seen at Figure 2 (positions 1 and 7). In fact, a strong evidence is clear: reconstructed positions are affected by inadequacies of the physical model introduced in MCNP simulations.

4. Conclusions

The RPT code has sensitivity to detect changes in the source positions caused by differences between its model of radiation detection system and that of MCNP code. A possible inadequacy in a CFD model of a process can cause distortions in some parameters of the flow. If one of these changed parameters is function of the velocities of the phase it is connected, uncertainties associated to measurements of this parameter can be evaluated by RPT tests. As a result, the RPT technique can be employed in the validation step of CFD simulations applied to the design of natural circulation safety systems of small modular reactors.

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